4.3 The September 1, 1992 Nicaragua tsunami

4.3.1 Introduction

On September 12, 1992 a catastrophic tsunami hit the Pacific coast of Nicaragua. The tsunami was triggered by an earthquake with an epicenter estimated about 100*km* offshore with a surface wave magnitude M_s estimated in the range $M_s = 7.0 - 7.3$ (Abe et al., 1993; Ide et al., 1993; and Satake et al., 1993). An extensive field survey was conducted two weeks after the event by an international tsunami survey team which reported maximum runup heights up to 10 meters and penetration distances up to half-a-mile into the dry land. The tsunami caused 168 deaths, 489 casualties and extensive property damage.

Imamura et al. (1993), Ide et al. (1993) and Satake et al. (1993) all reported a large discrepancy between the low surface wave magnitude (M_s) and the large measured runup heights. Satake et al. (1993) estimated a tsunami earthquake magnitude of $M_t = 8.0$ and they characterized this earthquake as a tsunami earthquake in the sense of Kanamori (1972).

Numerical modeling of the tsunami generation and propagation was carried out shortly after the event (Imamura et al., 1993), and the international survey team actually used some of their predictions in planning the survey. The model used linear shallow-water-wave theory without calculating wave runup; the calculations stopped at the 10m contour and the wave runup was estimated by multiplying the wave height at the 10m contour by a factor of two. The numerical values of these predictions were considerably different than the field observations, even though the relative distribution of “runup” values along the shoreline was approximately correct, i.e., the model predicted correctly the hardest hit areas, without predicting correctly the runup amplitudes. These computations suggested that perhaps the conventional method of estimating the source parameters from seismic data may not predict accurately the bottom displacement that generated the wave; any calculations using incorrect bottom displacements are unlikely to produce good agreement with the field data.

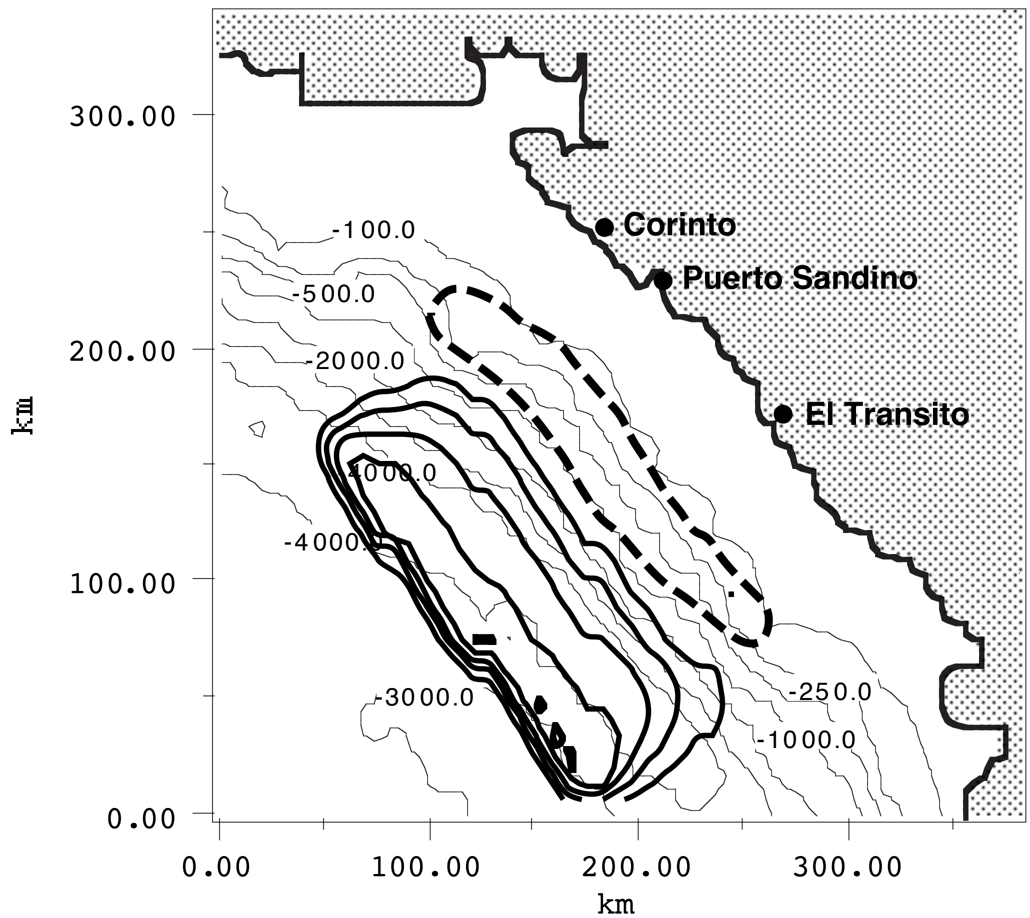

Figure 4.34 Contours of the sea-floor displacement for the Nicaraguan tsunami.

To improve their numerical predictions, Imamura et al (1993) re-evaluated their source parameters by comparing the field observations with the model results. They found that they could obtain a satisfactory agreement if they multiplied the model results by a factor of 10 and they conjectured that—since they were solving a linear problem—they should multiply the seismic moment as obtained by the Harvard CMT solution by a factor of 10. Preliminary unpublished results suggested that their calculation with the "improved" seismic moment did not produce substantially better agreement between the model and the field data and the results still differed by large factors. These observations suggest that perhaps the linear model stopping at the $10m$ contour is not an equally reliable method as the nonlinear model for calculating runup heights.

Titov and Synolakis(1993) then used a hybrid method, i.e. a combination of a 2+1 model and a 1+1 shoreline calculations by observing that the Nicaraguan offshore topography is essentially two-dimensional with little longshore variation in the region of interest.

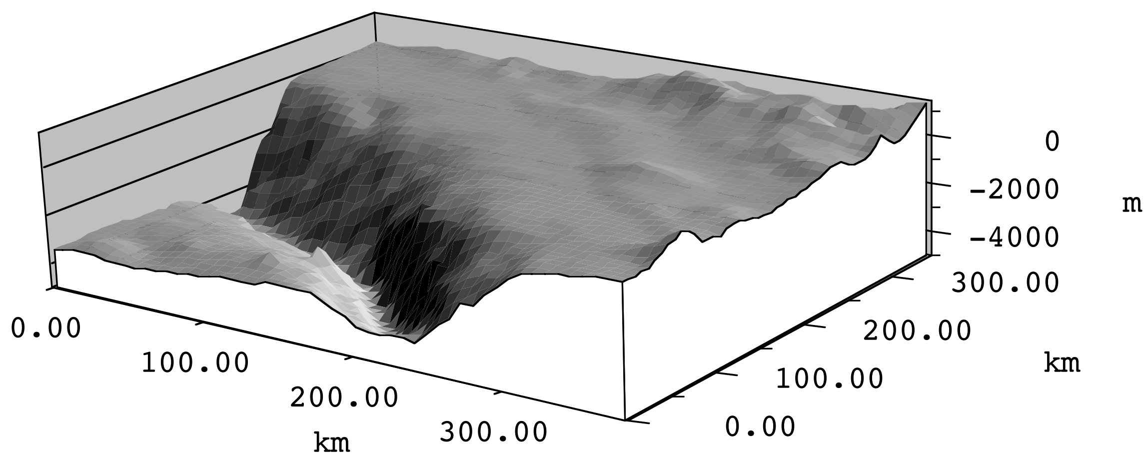

Figure 4.35 Bottom profile near the Nicaragua coast.

4.3.2 Numerical model

The objective of this study is to predict the coastal effects of the Nicaraguan tsunami with the bathymetry data available at the time of the writing of this paper from hydrographic charts which at best can be digitized only to a $1.5km$ grid. This type of coarse grid cannot predict correctly the details of the runup motion on the shoreline which invariably is a strong function of the local features. For example, in the village of El Transito, Nicaragua, the international survey team measured runup heights ranging from $6.4m$ to $9.9m$ (Satake et al., 1993). El Transito was completely inundated up to $1km$ inland. Interestingly, unpublished observations near the south side of the beach reported runup heights as low as $1.8m$, all within a length of $1km$. Also, at the town of Playa Hermoza, less than $3km$ from El Transito, even the beach umbrellas were found standing, a fact which caused a lot of interest in the local papers. Significantly lower runup heights were measured in other beaches north and south of El Transito. Since as Figure 4.35 shows, the coastline has the profile of a long plane beach, these observations suggest wave focusing at El Transito.

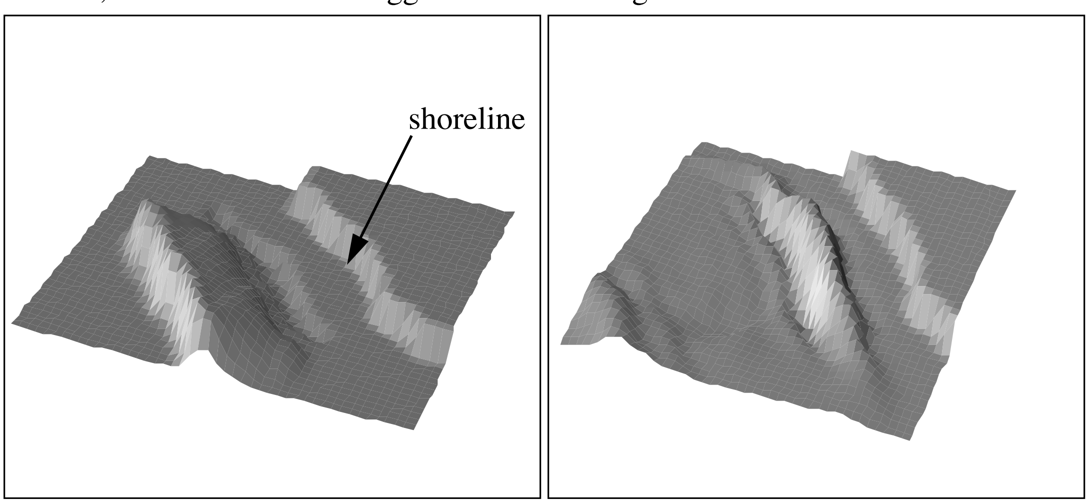

Figure 4.36 Three dimensional wave profiles over the bathymetry from Figure 4.35 at 25 sec and at 4 min 20 sec after generation for the 1992 Nicaraguan tsunami using 2+1 model.

Clearly, without detailed relief data, it is unavailing to attempt to model the two-dimensional shoreline motion. In fact to address this problem of scarce bathymetric data, an NSF survey team led by Synolakis went back to Nicaragua in the spring of 1995 to perform a bathymetric survey and generate more accurate data to resolve the riddle of the vastly different damage patterns between adjacent beaches. Until this data becomes available, it was conjectured that a 1+1 inundation calculation might provide valuable insight since the lack of significant offshore variation in the longshore direction might have allowed an eventually plane wave to attack the beach, permitting the use of the 1+1 model of chapter 2 close to the shoreline.

This hypothesis was tested as follows. The static deformation of the bottom was calculated using the elastic model of the earthquake source (Gusyakov, 1978) with a ten times larger moment than estimated from the seismic data. These parameters were a strike angle of 302°, a dip angle of 16°, a slip angle of 87° and a seismic moment of $3.0 \times 10^{20} Nm$. The fault plane was estimated from the aftershocks-distribution to be about $200 \times 100 km^2$, and the average dislocation was estimated about $3.75m$. shows the three-dimensional wave profiles at the initial instant of the earthquake and at 4 min 20 sec after generation. Figure 4.36 shows that after 4 minutes of propagation—when the tsunami reaches the shelf area—the wave front becomes almost parallel to the shoreline and it is fairly straight-crested, suggesting that down to the resolution of this model, the wave reaches the coastline of Nicaragua, very similar to a plane wave approaching a plane beach. Assuming that there is little wave dispersion and diffraction at the north and south boundaries of the calculation, it is reasonable to treat the shoreline evolution as a two-dimensional problem, with initial data provided by the 2+1 model.

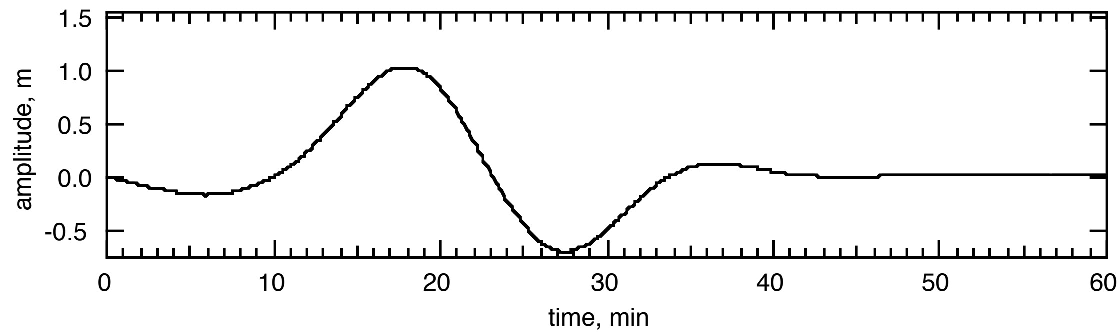

Figure 4.37 The waveform computed by two-dimensional model at 200 m depth contour. This profile was used as an input for the runup computation at El Transito.

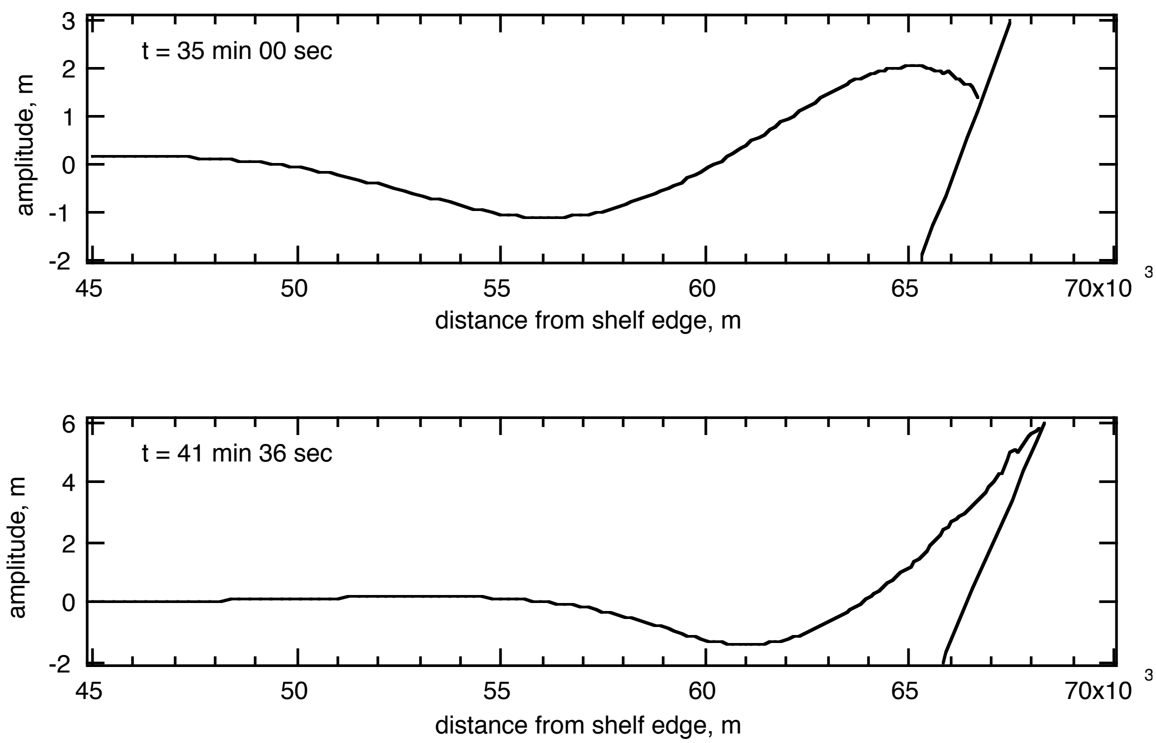

Figure 4.38 The wave profiles for two different times computed by the two-dimensional model using the waveform shown on Figure 4.37 as input.

As an example, Figure 4.37 shows the wave profile used as input for the two-dimensional model calculations for El Transito. This is the profile resulting from the 2+1 calculations from the 200m contour. Figure 4.38 shows the same wave 35 minutes later, after breaking and the wave profile near maximum runup. The comparison among computed and measured runup heights along the Nicaraguan shore using this procedure is shown in Figure 4.39.

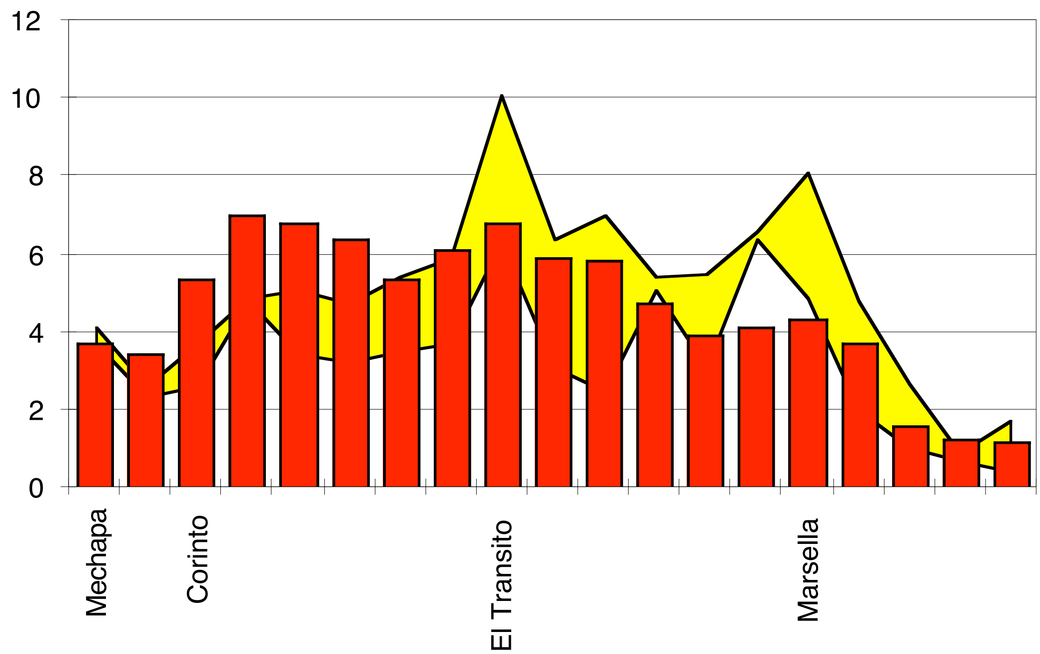

Figure 4.39 The comparison among the computed and measured runup heights along the Nicaragua coast. Black bars are computed results; two lines with a shadow area between them are maximum and minimum measurements at the site.

The model results are in fairly good agreement with the field observations, suggesting that for simple topographies like in the Pacific Coast of Nicaragua, a combination of three-dimensional and two-dimensional nonlinear models may be more effective method for estimating wave runup than simpler linear models which predict wave runup based on the wave height at the 10*m* contour.

4.4 The February 21, 1996 Peru tsunami

4.4.1 Introduction

On February 21, 1996 at 12:51 GMT (7:51 local time), a large earthquake occurred at 9.6S, 80.2W approximately 240*km* off the coast of Peru. The earthquake had a Harvard estimate of $M_w = 7.5$ and a USGS estimate of $M_w = 7.3$. The available data suggest a low-angle thrust subducting the Nazca Plate beneath the South American plate with complex and relatively slow rupture characteristics. The tsunami resulting from this quake impacted more than 300*km* of the Peruvian coast causing 12 fatalities, numerous injuries and property damage.

4.4.2 Notes on the post-tsunami survey

The International Tsunami Survey Team surveyed the areas of the tsunami attack along the Peruvian coast one month after the event, between March 15 and March 22. The coast of Peru in the affected area is arid with areas of wind-blown sand. The beaches are of two main types: wide fairly plane beaches with very flat slopes and sheltered curved beaches anchored by rocky outcrops. The curved beaches usually have somewhat more steep slopes. Since there is very little vegetation outside of irrigated areas near the rivers, traditional evidence of tsunami passage such as dead vegetation in the areas inundated with salty sea water, marks on trees were usually absent. Runup heights were often based primarily on the evidence of debris lines which in this region can be easily erased by the blowing sand. Runup heights generally varied between 2 to 3*m* except in areas where there was some topography to focus the tsunami. At the Port of Chimbote the tsunami was affected by the local topography so that it inundated the landward 800*m* of a dock leaving the seaward 200*m* dry overturning a truck and transporting a steel guard shack for a distance of 20 m.

Although the runup heights were not extremely high, inundation distances were often quite large because of the flat beach slopes. Several of measured inundation distances were well over 200*m*. At Ensenada La Posa the tsunami inundated an entire isthmus, approaching from both sides to cover a distance of 1500*m* and carrying fishing boats 300*m* onshore. At each survey location the team attempted to measure inundation distance and runup elevation with respect to current sea level and where appropriate survey a detailed transect of the runup area. Sediment characteristics were observed and in several locations trenches were dug to obtained more detailed data. Eyewitnesses generally reported that the shaking due to the earthquake was mild. In some instances near the northern part of the survey area, the shaking was not noticed by everyone. The interviewees generally reported the appearance of the wave as black with no indications of breaking. Occasionally a hissing sound associated with the wave was mentioned. People recalled either two or three waves with the second being the largest. The time between the three waves varied and was generally accepted to be near eight minutes at the town of Coishco.

4.4.3 Numerical model

This event was modeled numerically using a combination of VTCS-2 and VTCS-3 using the same concept as for the Nicaragua simulation, again due to lack of quality bathymetric data. The source of the bathymetric data used for the computation was 5*min* gridded digital bathymetry (TOPO-5) available from NOAA through Internet. This gridded data were corrected in the near-shore area using nautical charts. The bathymetry used for the computations was interpolated from the corrected 5*min* data to obtain the resolution of 600*m* in nearshore areas. In the coarse 5*min* data, the small-scale features of the nearshore bathymetry were lost between grid points. Without these local features computing the runup process does not add any accuracy to the final solution. Therefore, no runup computations in the large-scale 2+1 computations were used; instead, a reflective-wall type boundary conditions along the shore was used. On the other hand, the survey team performed several surface transect measurements in selected locations, and it obtained high quality 2-D topographic data at the places of the runup measurements. These data were used for the high-resolution 1+1 runup computations.

The source mechanism for the large-scale 2+1 simulation was approximated as a double couple model with a single rectangular plane rupture. The fault mechanism was derived from the Harvard CMT solution. The size and the location of the fault rupture was estimated from the distribution of the aftershocks. Several trial computations were performed changing slightly the location and the average slip amount of the source to obtain the distribution of the computed wave heights similar to the measured runup heights. The final source parameters are, a strike angle of 340˚, a dip angle of 15˚, a slip angle of 96˚, average dislocation of 4*m* and a source area of $120 \times 60 km^2$. This source produces static displacement of the sea floor with maximum uplift of 1.8m and maximum subsidence of 0.7*m*. The contours of the source deformation are shown on Figure 4.40. The source produces a leading-depression wave (Tadepalli and Synolakis, 1994, 1996) propagating toward the shoreline in the area between Huanchaco and Huarmey, consistent with eyewitness reports. Outside this area, the computations show a positive wave reaching the shoreline first.

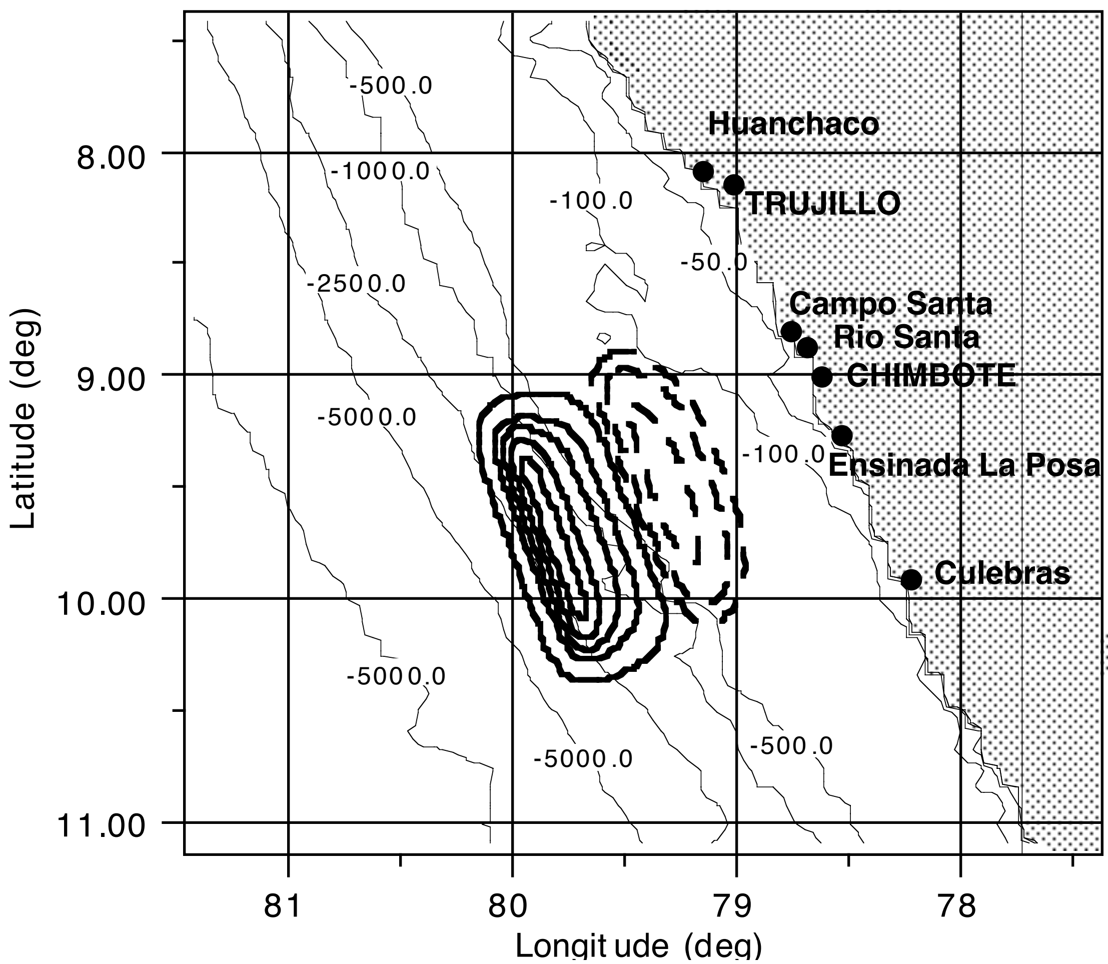

Figure 4.40 Contours of the sea bed displacement of the Peru earthquake that were used as a tsunami source for the 2+1 computations.

The tsunami formed a wave-front parallel to the shoreline very quickly after the generation. Figure 4.41 shows a comparison of the computed tsunami heights using both a threshold model and a hybrid model with the runup measurements. There are two locations where the discrepancies between the model and measurements are especially large. On the south, the runup at Culebras was measured as high as 5 meters. Only one runup measurements (rated B in the scale of Synolakis et al, 1994) was found at that high altitude, therefore it can be considered as a very localized splash. The model with 600*m* grid resolution is not expected to reproduce such effects.

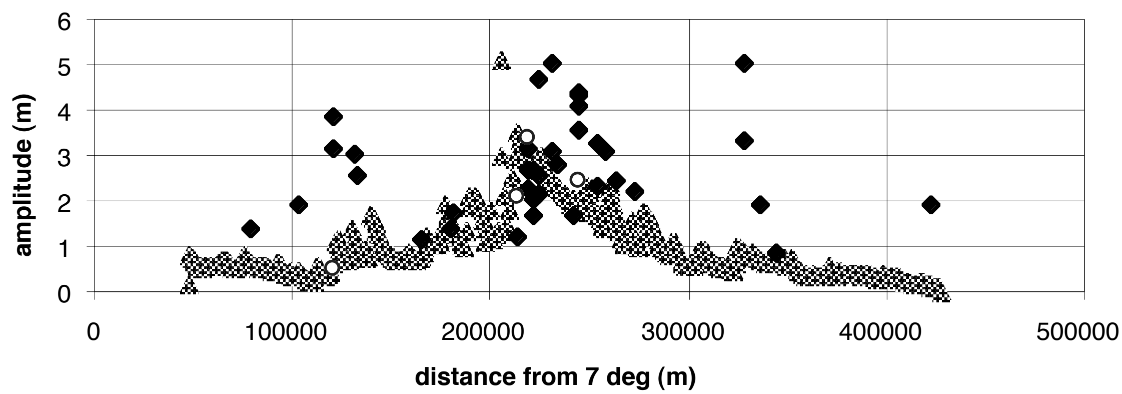

Figure 4.41 Comparison between measured runup heights (black diamonds), computed with a threshold 2+1 calculation (grey triangles) and computed runup values using a hybrid 2+1 and 1+1 model (empty circles).

On the north, the area near Trujillo show a distinct local maximum in the runup distribution. The model shows some wave focusing effect in this area and computes a local maximum in the distribution of runup heights. However, the difference with measurements is larger than in other locations. The computations with several different source locations and sizes have not changed significantly the computed wave maximum in that location. It means that localized wave refraction driven by the local bathymetry plays a principal role in forming wave amplitudes. The low resolution bathymetry used for the study could be a source of the discrepancies. Another explanation could be a more complicated source mechanism with several sub-faults. Additional studies with a higher resolution bathymetry and topography data are necessary to resolve these questions.

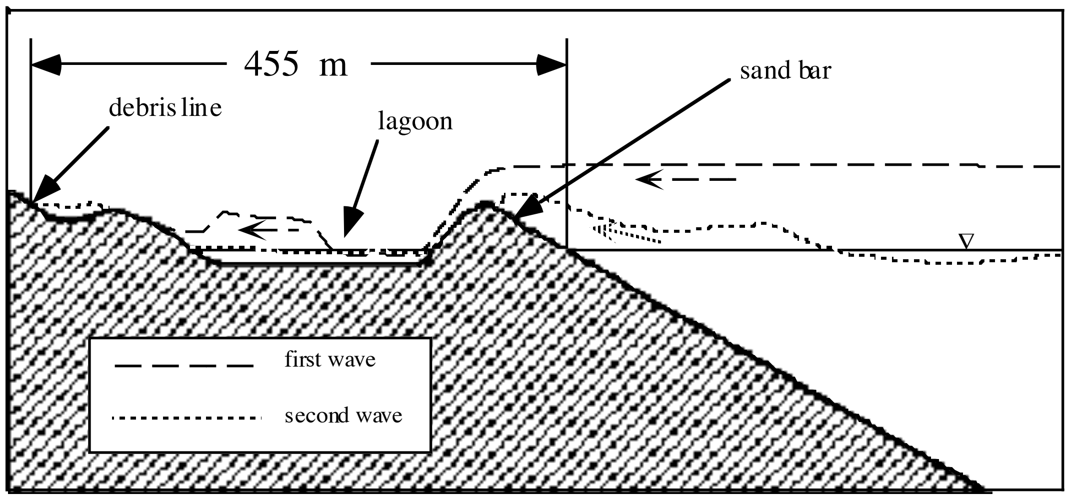

Figure 4.42 Surface profiles computed with 1+1 runup model of the tsunami inundation in Campo Santa

Figure 4.41 also shows the results of the hybrid runup computations. The runup modeling was performed at 4 locations where the survey team measured beach profiles. The wave-record computed by the 2+1 model at the depth of 100*m* for each location was the input for the 1+1 inundation computations. The main assumption of these computation is that the tsunami is a plane wave when it reaches the 100*m* contour. The runup modeling includes the computation of the wave climbing up the dry beach with the grid resolution up to 20*m* in the cross-shore direction on the dry land. The runup computations produced vertical runup values similar to the ones computed by the 2+1 model. Also, in addition to the vertical runup the 1+1 model computes the dynamics of the wave climbing up the beach profiles and the horizontal propagation distances. Despite the simplified assumption of the 1+1 calculations, the model performed very well in reproducing the wave penetration distance in several locations with complicated beach profiles, as shown in Figure 4.42, which shows the calculated evolution of the tsunami wave climbing up the beach in Campo Santa.

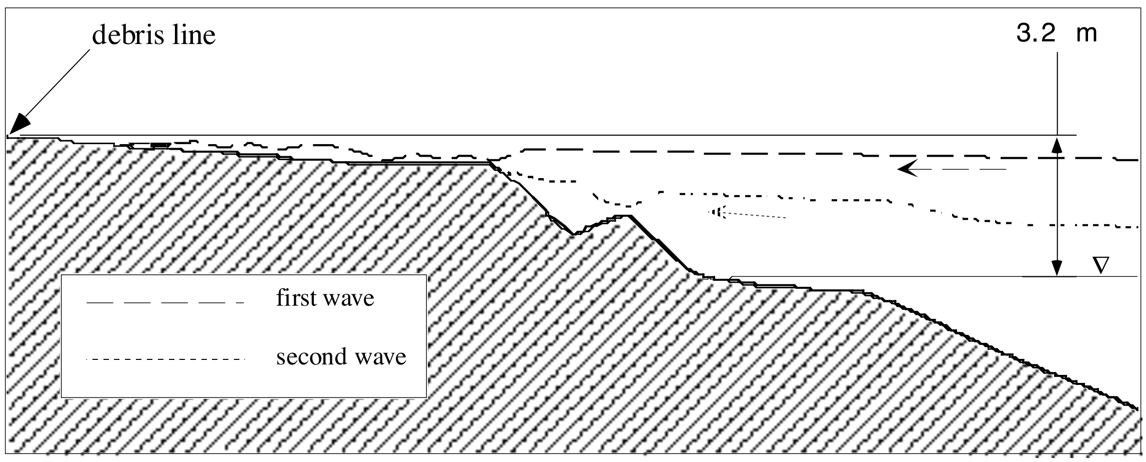

Figure 4.43 Surface profiles computed with 1+1 runup model of the tsunami inundation in Rio Santa

The runup mark was found in this location as a line of debris stretched along the shoreline on the distance of 455*m* inland from the water level. The on-shore topography there features a lagoon extended along the shoreline with a bottom level lower then the ocean water level. The debris line was found on the opposite side of the lagoon on the height of 1.21*m* from the waterline at the time of the earthquake. Figure 4.42 demonstrates how the 1+1 model simulates the flow over the sand bar and the wave propagating into the lagoon. The computed value of the runup is 1.9*m*, a little higher then measured, the computed distance is more than 500*m* from the shoreline, where the wave reached the boundary of the computational area. Interestingly, after the model's first and second wave withdrew from the lagoon, the water stayed on the level of the debris line forming a pool of water on the level higher than the ocean water level (see Figure 4.42). This result might indicate that the debris line was actually formed not by the highest tsunami wave inundation. Instead, the new water-pool formed by the tsunami wave and filled with carried-on debris, might have created a debris line on its shore. In fact, the eyewitness in that location mentioned the wave penetrating further then the debris indicate. But the report was very erratic and was not confirmed by observations, so the debris evidence was taken as the runup height.

The computed values in Rio Santa are also close to the measured ones: measured penetration is 364*m*, the computed is 390*m*; the measured runup is 3.2*m*, computed is 3.4*m*. The evolution of the wave climbing up the beach in Rio Santa, as computed with the 1+1 model, is shown in Figure 4.43. The calculation showed that the first wave climbed up the beach step near the shoreline and penetrated deep into the potato field on the top. The second wave was not high enough to overtop the beach step.

The beach profiles of the other two modeled locations—Ensinada La Posa and Huanchaco—are not as complex as the previous two. Nevertheless, the runup computation are not as close to measured values there. The 2+1 simulation showed a large difference between measured and computed runup in that locations also.